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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : G02F 1/025

A1

(11) International Publication Number: WO 00/49451

(43) International Publication Date: 24 August 2000 (24.08.00)

(21) International Application Number: PCT/GB00/00531

(22) International Filing Date: 16 February 2000 (16.02.00)

(30) Priority Data:
9903339.1 16 February 1999 (16.02.99) GB

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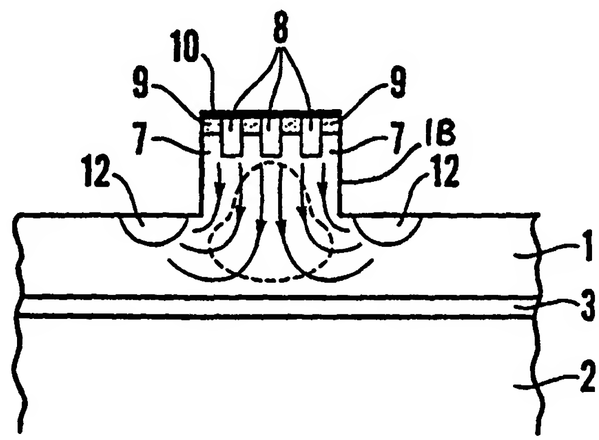
(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

**Published**
*With international search report.*

(54) Title: CONTROLLED OPTICAL WAVEGUIDE

(57) Abstract

An optical waveguide, such as a rib waveguide, having a first portion (7) to which a dopant (9) and/or a metal layer (10) is applied to enable an optical property of a second portion of the waveguide to be altered, the first portion (7) having a structure, e.g. being corrugated, the geometry of which is such as to prevent an optical wave being carried in the first portion (7). The dopant (9) and/or metal layer (10) can thus be positioned close to the second portion which carries the optical wave without causing perturbation, e.g. attenuation and/or polarisation, of the optical wave.



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# CONTROLLED OPTICAL WAVEGUIDE

## TECHNICAL FIELD

The invention relates to an optical waveguide having a region to which interacting means, such as a dopant or electrode, are applied for controlling an optical property of the waveguide.

## BACKGROUND PRIOR ART

It is known to apply dopant to a portion of the waveguide, for instance to form a p-n or p-i-n diode across the waveguide for injecting charge carriers into the waveguide and thus altering the effective refracture index of the waveguide. By this means a phase modulator can be provided for example as disclosed in WO95/08787. However, in designing such a device, a compromise has to be made between the desire to maximise the overlap between the charge carriers injected into the waveguide and the optical mode therein whilst minimising the attenuation caused by overlap between the optical mode and the doped regions.

It is also known to apply a metal layer to a waveguide, e.g. to provide an electrical contact, or a heating element thereon. Again, there is a desire to position this as close as possible to the optical mode to maximise the effect of the electrical contact and/or heating but, on the other hand, the metal layer needs to be spaced from the optical mode so as to minimise absorption of one or both of its constituent TM or TE modes by the metal layer.

There thus remains a need to be able to apply interacting means, such as dopant or an ohmic contact, to a waveguide without the interacting means itself causing substantial perturbation, such as attenuation or polarisation, of an optical wave carried by the waveguide.

The present invention aims to provide a solution to this problem.

## SUMMARY OF THE INVENTION

Thus, according to th present invention, there is provid d an optical waveguide having a first portion to which interacting means are applied to nable an optical property of a second portion of the waveguide to be altered via said interacting means, the first and

second portions ach b ing formed of a light conducting material, the first portion having a structure the geometry of which prevents an optical wave being carried thereby, whereby the interacting means can be positioned in close proximity to the second portion without the interacting means itself causing a substantial perturbation of an optical wave carried by the second portion of the waveguide.

Other features of the invention will be apparent from the following description and from the subsidiary claims of the specification.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be further described, merely by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic cross-sectional view of a known form of diode formed across a rib waveguide;

Figure 2 is a schematic cross-sectional view of a known arrangement of a heating element applied to a rib waveguide;

Figure 3 is a schematic cross sectional view of an optical waveguide according to a first embodiment of the invention;

Figure 4 is a schematic cross-sectional view of an optical waveguide according to a second embodiment of the invention; and

Figure 5 is a schematic perspective view of an optical waveguide according to a third embodiment of the invention.

BEST MODE OF THE INVENTION

Figure 1 shows a rib waveguide formed in a silicon layer 1 which is separated from a silicon substrate 2 by an insulating layer 3 of silicon dioxide. Such waveguides are described further in WO95/08787 and the references given therein. A diode can be formed across the waveguide by providing a doped region on each side thereof, e.g. a p-doped region 4 on on side of the waveguide and a n-doped region 5 on the other side thereof, e.g. to form a phase modulator. The doped regions may be formed in the top surface of a slab region 1A of the silicon layer 1 on either side of the rib 1B formed

th rein as shown in Figure 1. It should be noted that with this form of waveguide, th waveguide is provided not just by the rib 1B but also the by slab region 1A beneath the rib and, to some extent, the slab region on either side of the rib 1B. This is shown by the position of the optical mode which is depicted by dashed lines in Figure 1. It will also be appreciated that an optical wave travelling along the waveguide also includes exponentially decaying portions extending both laterally and vertically from the concentrated part of the optical mode illustrated in the Figure.

It should be noted that the devices shown in the Figures would usually have an oxide layer formed over the silicon layer but this is not shown in the Figures.

The arrangement shown in Figure 1 is preferred to an arrangement in which the doped regions are provided in the side faces of the rib 1B as, by positioning the doped regions in the slab regions either side of the rib, overlap between the doped regions and the optical mode is reduced. Nevertheless, part of the optical mode, and in particular the exponentially decaying part of the wave on either side thereof may still be attenuated to some extent by the presence of the doped regions. Furthermore, the positions of the doped regions in the slab regions on either side of the rib, leads to a less than optimal overlap between the injected charge carriers and the optical mode, as a significant proportion of the current between the doped regions 4 and 5 passes beneath the concentrated area of the optical mode. The current paths from the p-doped region to the n-doped regions are shown by arrows in Figure 1. To improve the overlap between the injected carriers and the optical mode, it would be preferable to provide a doped region on top of the waveguide rib 1B, e.g. a p-doped region, and complementary doped regions in the slab regions on either side of the rib 1B, e.g. n-doped. However, a disadvantage of such a structure is that the overlap between the optical mode and the doped region on top of the rib 1B would introduce unacceptable attenuation of the optical mode.

Figure 2 also shows a rib waveguide formed in a silicon-on-insulator (SOI) chip in this case with a metal layer 6 and oxide layer 6B formed thereon. The metal layer may be used as a resistance heater to heat the waveguide for example to form a thermal modulator. However, unless the oxide layer 6B is thick, the metal layer 6A absorbs a portion of the optical mode travelling in the waveguide, .g. the TM mode, and thus causes polarisation of the wave. If a thick oxide layer 6B is used, this greatly reduces the effect of the heater as the oxide has a relatively low thermal conductivity.

Figure 3 shows a phas modulator according to an embodiment of the invention which helps overcome the problems discussed in relation to the modulator shown in Figure 1. This is achieved by modifying the structure of a first portion of the waveguide to which the dopant is applied, in the example shown, this being the upper surface of the rib 1B, by forming corrugations therein. The illustrated embodiment comprises four corrugations 7 with three grooves 8 therebetween. The geometry of the corrugations 7 is such that their effective refractive index is too low to allow the optical mode guided by the rib to penetrate into the corrugations. The optical mode carried within a second portion of the rib waveguide, in this case the region beneath the corrugated region, is thus excluded from the corrugated region of the waveguide. Doped regions 9 can thus be formed in the corrugations 7 in close spacial proximity to the optical mode but will not interact optically with the optical mode in the second portion of the waveguide as the optical mode is excluded from the corrugations.

The doped regions provided in the corrugated portion of the waveguide may be p-doped, and n-doped regions 12 may be provided in the slab region on either side of the rib 1B. In this way, doping the top of the waveguide rib 1B can be achieved without introducing significant further loss and the current flow between the doped regions 12 and the doped regions 9 passes through a much greater proportion of the optical mode and so has a greater effect thereon as shown in Figure 3.

Alternatively, the n-doped regions may be provided in further corrugated regions (not shown) provided in the slab region on either side of the rib 1B and/or on the side faces of the rib 1B, or may be provided on the underside of the waveguide.

The doped regions are preferably formed by implantation as this enables the depth of penetration of the dopant into the silicon to be carefully controlled and thus kept low. Diffusion doping can, however, be used if a short drive in period is used. The majority of the dopant is preferably contained within the upper half, or less, of the height of the corrugations 7. The concentration of dopant falls gradually from the upper surface of the corrugations so does not have a distinct lower boundary. However, the transition from a high concentration of dopant to a low level of dopant preferably occurs about half way down the corrugation, or at a higher point, so the lower half of the corrugation has relatively little dopant in it. Preferably, no dopant extends beyond the point where the corrugations 7 meet the remainder of the waveguide rib 1B.

The doped region 9 can be contacted by a metal layer provided on the distal or upper surface of each corrugation 7 or a single metal layer 10 may be provided across the upper surfaces of the corrugations 7 if the grooves 8 therebetween are filled with some other material of sufficiently low refractive index, such as silicon dioxide or a polymer such as polymethylmethacrylate (PMMA), which acts as a cladding rather than a light conductor. The metal layer 10 does not absorb part of the optical mode as the optical mode is effectively excluded from the corrugated region of the waveguide, as described above.

In a similar manner, a thermal modulator can be formed as shown in Figure 4, with a corrugated region on the upper surface of the rib 1B, with the grooves 8 filed by silicon dioxide or PMMA, and a metal layer 11 in the form of a resistance heater applied across the upper surface of the corrugations 7. The thermal conductivity of the corrugated region is significantly improved compared to the arrangement shown in Figure 2 in which an oxide layer (having poor thermal conductivity) is provided between the metal layer 6 and the rib 1B to reduce the perturbation caused by the presence of the metal layer.

A rib waveguide in an SOI chip, is typically around 4 microns high, measured from the silicon dioxide layer (and excluding the corrugations), and around 4 microns wide. In this case, the three grooves 8 would typically be about 0.35 to 1.0 microns wide and about 0.35 to 1.0 microns deep. The size of the corrugations 7 would fall in the same range; the grooves 8 and corrugations 7 preferably being of a similar width. The width and depth of the grooves, the number of grooves (and hence the number of corrugations) and the width of the corrugations will, however, depend on the dimensions of the waveguide and their geometry is selected so as to ensure no, or very little, optical power is carried in the corrugated portion of the waveguide. With light having a wavelength in the range 1.2 to 1.7 microns, the corrugations should preferably have a width of 0.5 microns or less.

The corrugated region may be formed by etching grooves 8 in the upper surface of the rib 1B (which is preferably made slightly taller to allow for this). Alternatively, the corrugated region may be formed by growing or depositing the corrugations 7 on the upper surface of the rib.

The corrugated region should comprise at least one corrugation or at least one groove but preferably a plurality of corrugations and/or groov s are provided so the doped regions are spread out rather than b ing too localised (which would lead to high current densities in a diode formed across the waveguide).

The corrugations and grooves in the embodiments described above are parallel to the waveguide axis but in other embodiments this need not be so. Grooves or corrugations may, for instance be formed across a waveguide as shown in Figure 5 which shows a rib waveguide similar to that of Figure 3 but with corrugations 14 extending across the upper surface of the rib 1B. The upper portions 15 of the corrugations 14 may then be doped and/or a metal layer (not shown) applied to the upper surface of the corrugated portion (with the grooves filled by silicon dioxide or some other material). It will be appreciated that grooves extending laterally across the waveguide reduce the effective refractive index of the corrugated region so light cannot travel therein. The dimensions and period of these grooves are preferably in the same range as for the embodiment described above in relation to Figure 3.

The above examples relate to a rib waveguide formed on a silicon-on-insulator chip. Similar arrangements may, however, be used with waveguides formed of other materials and other forms of waveguide, e.g. a slab waveguide, provided they permit the formation of a structure the geometry of which prevents light being carried thereby.

Other structures having a geometry which excludes light from a region of the waveguide may also be used beside the corrugations described above, e.g. a lattice of grooves or of corrugations. The periodic nature of the structure may also be regular or irregular.

## CLAIMS

1. An optical waveguide having a first portion to which interacting means are applied to enable an optical property of a second portion of the waveguide to be altered via said interacting means, the first and second portions each being formed of a light conducting material, the first portion having a structure the geometry of which prevents an optical wave being carried thereby, whereby the interacting means can be positioned in close proximity to the second portion without the interacting means itself causing a substantial perturbation of an optical wave carried by the second portion of the waveguide.

2. An optical waveguide as claimed in claim 1 in which the structure comprises a corrugated region of the waveguide comprising at least one corrugation or at least one groove.

3. An optical waveguide as claimed in claim 2 in which the corrugated region comprises a plurality of corrugations and/or grooves.

4. An optical waveguide as claimed in claim 2 or 3 in which each corrugation has a width in the range 0.35 to 1 micron.

5. An optical waveguide as claimed in any preceding claim in which the interacting means comprises dopant applied to the first portion of the waveguide.

6. An optical waveguide as claimed in claim 5 and any of claims 2-4 in which the dopant is applied to the or each corrugation.

7. An optical waveguide as claimed in claim 6 in which the or each corrugation has a height in the range 0.35 - 1.0 microns.

8. An optical waveguide as claimed in Claim 6 or 7 in which the majority of the dopant is contained within the upper half, or less, of the height of the or each corrugation.

9. An optical waveguide as claimed in any preceding claim in which the interacting means comprises a metal lay r.

10. An optical waveguide as claimed in Claim 9 and any of Claims 2-4 in which the metal layer is applied to a distal surface of the or ach corrugation.

11. An optical waveguide as claimed in Claims 9 and 10 in which the or each groove is filled with another material and the metal layer extends across the distal ends of the corrugation and across the filled grooves between the corrugations.

12. An optical waveguide as claimed in Claim 5 or any claim dependent thereon in which a diode is formed between the dopant applied to the first portion of the waveguide and dopant applied to another region of the waveguide.

13. An optical waveguide as claimed in Claim 12 in which the diode forms part of a phase modulator.

14. An optical waveguide as claimed in Claim 2 or any claim dependent thereon in which the said at least one corrugation or at least one groove is parallel to the optical axis of the waveguide.

15. An optical waveguide as claimed in Claim 2 or any of Claims 3 to 13 when dependent thereon in which the plurality of corrugations and/or grooves extend across the waveguide.

16. An optical waveguide as claimed in any preceding claim in the form of a rib waveguide.

17. An optical waveguide as claimed in Claim 16 in which the first portion of the waveguide comprises an upper portion of a rib of the rib waveguide.

18. An optical waveguide as claimed in any preceding claims formed on a silicon-on-insulator chip.

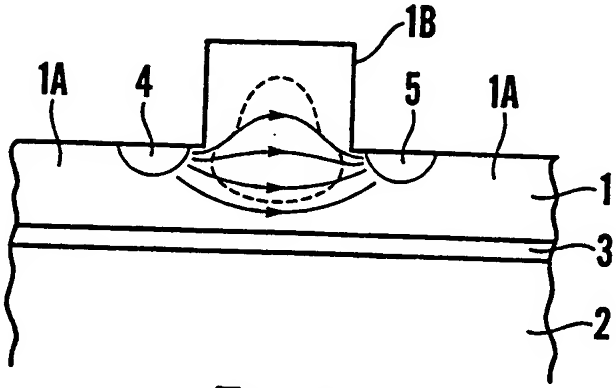


Fig.1

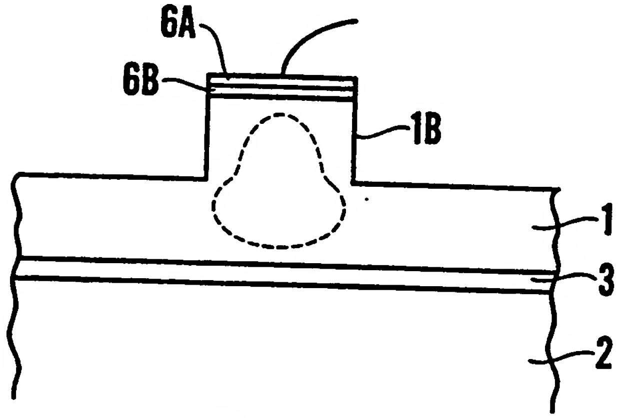


Fig.2

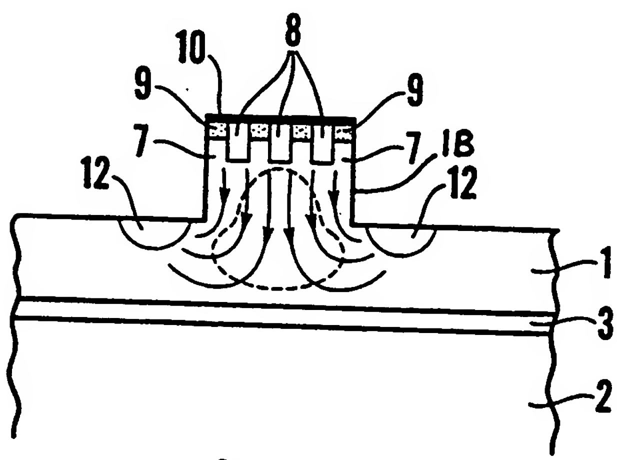


Fig.3

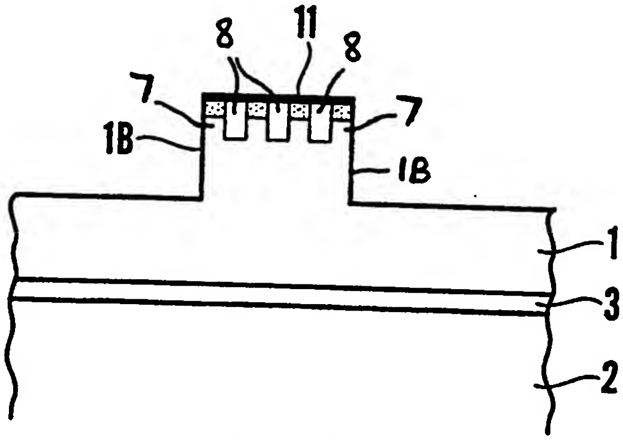


Fig.4

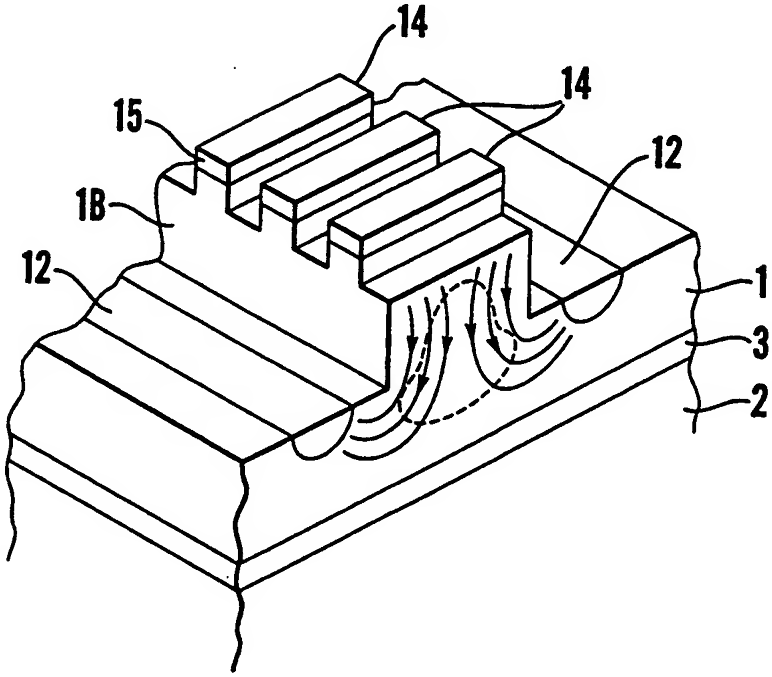


Fig.5

# INTERNATIONAL SEARCH REPORT

International Application No
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**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 7 G02F1/025

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

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**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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